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PARTIAL MASS ISOLATION IN TALL BUILDINGS

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SUMMARY

To find an economical approach in the seismic design of tall buildings, it is proposed to isolate a part of the structure by an isolator layer located in the height of building. Application of this technique causes a fundamental change in basic dynamic characteristics of the system. As a result, all major modal shapes of structure exhibit large displacement at the level of the isolator. A viscous damping device integrated into the isolation layer utilizes this relative movement to effectively reduce the earthquake input energy transmitted to the system. This technique is quite versatile and easily adjustable to different applications including seismic retrofit of buildings. Numerical analysis of some basic examples in this study shows desirable performances for a variety of applications. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS: partial isolation; tall buildings; earthquake design

1. INTRODUCTION

During an earthquake, a certain amount of energy transfers to the structure. This earthquake input energy changes into inertial and potential form and will be gradually consumed by damping forces in the process of vibration. Depending on how fast and effective damping mechanism dissipates the input energy, the amplitude and duration of vibration reduces and structural performance of the system improves.

Base-isolation technique is a well-known approach in seismic design of low-rise buildings. This method effectively reduces the input energy transmitted to the structure by lengthening the first natural period of the system. In this case the additional required flexibility is provided by an isolator layer located at the level of foundation with a small stiffness compared with the stiffness of actual building. Large flexibility in the isolation mechanism reduces the contribution of elastic deformation of the structure in the process of vibration and results in a system subjected to smaller earthquake forces.

Behaviour of a base-isolated building is dominated by its first natural mode. Consequently, the energy content of higher modes (the only modal shapes in a base-isolated structure requiring considerable amount of elastic deformation) in dynamic response of these systems would be negligible. Input energy of the first mode is predominately dissipated by hysteretic damping in the isolation mechanism and only a small fraction of it transfers to the structural components of the building.

This powerful technique, however, is not applicable in high rises and medium height buildings for technical reasons. The natural period of these structures are relatively long and changing the first mode of vibration

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(also removing the higher-mode effects) requires a large flexibility in isolation mechanism. This is considered a major technical problem, especially if a large misalignment of vertical force on the isolator is expected. Vertical stiffness of the isolator is also a technical concern. Tall buildings are no longer shear-dominated structures and the bending moment at the foundation level is not negligible. In these structures, a vertically stiff isolation mechanism is required to prevent development of an undesirable rotational degree of freedom at the base of building. The existing technology can hardly provide a vertically stiff isolator capable of carrying the weight of building with a considerable misalignment and still rendering a large horizontal flexibility. Moreover, the enormous weight of tall structures requires utilization of a large number of isolators in the design of buildings which may not be considered economical.

Since reduction of input energy by base isolation in tall buildings is not practical, the remaining choice is to properly damp this energy in the structure. Damping of input energy requires either a sophisticated and effective damping mechanism or it needs a large elastic deformation capacity in structure to be able to store input energy elastically and damp it gradually by inherent damping of structural members. The latter choice requires a large volume of structural material which is not practical in tall buildings due to increase in weight and volume of the structural components of the system.

In an earthquake, structures with long natural period usually experience rather small acceleration and forces, but, they are still subjected to high velocity. In fact, earthquake velocity response spectrum sometimes has another peak at the range of a tall building's natural period. This phenomenon although seems undesirable (because earthquake input energy is proportional to velocity), alternatively it can be viewed as a potential source in reducing seismic effects on tall structures.

Viscous damping in a structural system is considered as non-conservative forces proportional to velocity. Therefore, wide-spread use of viscous devices in structures with long natural period is an effective way in dissipation of input energy in these systems. Although this fact has been known for years and is in practice in designing of high-rise structures, it is still difficult to substantially increase the damping ratio of tall buildings by this approach. Demanding provisions to keep lateral drift of tall structures at a certain small level, does not provide the required large differential relative velocity in any part of the system to effectively dissipate earthquake input energy through viscous damping devices.

Using hysteretic damping is not practical and also not effective in tall buildings. A long natural period in a structure is virtually an indication of a system dominated by inertial rather than potential forces. In this case inertial energy in the structure transforms to potential form with only a small force but large deformation. This mechanism of behaviour does not allow an effective hysteretic damping to be implemented in the structure, unless a large plastic deformation occurs. The importance of high-rise buildings and the potential of P–Δ effect usually do not allow large plastic deformation of structural members to take place. Moreover, since tall buildings are already in the range of long natural periods, the advantage of plastic behaviour of members in lengthening the natural period of the structure is not considered beneficial to the system's behaviour (while it is a desirable feature in reducing seismic effects on short buildings).

A more sophisticated approach in the design of tall structures is to use active control systems to improve the structural performance of the building (during earthquake and/or wind) by application of automated control devices. Although this is an admissible approach for high-rise structures, it is not considered suitable for the range of medium height to tall buildings due to problems associated with cost and maintenance of the system.

The method proposed here, improves the performance of tall buildings by integrating both concepts of input-energy reduction and viscous damping enhancement in a unified criteria. Preliminary results indicates an impressive improvement on the behaviour of almost all types of tall buildings subjected to a variety of earthquakes. The method is predominantly a passive-design approach for medium height tall buildings but integration with active control systems can boost its application to tall high-rise structures. Among other applications, the possibility of using this technique in earthquake retrofit of existing low- and high-rise buildings is quite promising.

2. MASS ISOLATION IN STRUCTURAL DYNAMICS

Base isolation in structural design of buildings is a term borrowed from mechanical engineers who use this technique to isolate the source of vibration (usually an engine or other vibrating devices) from its supporting structure. The same conception is used by civil engineers to isolate buildings from the earth as the source of vibration. However, to isolate the source of vibration is not necessarily the only way to reduce vibrational effects by isolation. This is obvious when the same base-isolated system is subjected to another source of vibration not from its base. As an example, base-isolated structures subjected to wind load can still benefit from the implementation of the isolation layer located at the foundation level.

Isolation is, in fact, a means to change dynamic characteristics of a vibrating system in transferring inertial energy to potential form, with less force on the structural components of the system but in the expenses of accepting additional deformation within the isolator. Therefore, the point of application of isolation could be wherever inertial energy is generating and/or where system can accommodate the required excessive deformation. A more effective implementation of this technique in multi-degrees-of-freedom systems can be adopted if the isolation layer applies where most of the inertial energy in the structure is building up. Thus, the point of optimal application of the isolator is wherever a sizable part of mass is subjected to high acceleration.

Base-isolation technique although very effective, it is somehow blind to the fact that, the most important part of mass in generating inertial force and energy in a building is located on the top portion of the structure. Figure 1 shows a hypothetical code-based approach in distribution of earthquake forces in a tall building with uniform mass. According to this simple example, more than 40 per cent of shear force builds up in about 20 per cent height of the structure. The percentage of contribution of the top portion of mass in generating structural forces is indeed more, if bending moment at the base of building is the main design parameter. In the same example 60 per cent of moment at the base of the structure is created by only 20 per cent of mass at the top, where the localized bending moment is only about 10 per cent of the base moment. Considering these facts, it seems rational if mass isolation applies only on the top portion of the structure. This technique hereinafter is referred to as Partial Mass Isolation (PMI) or in brief, Partial Isolation.

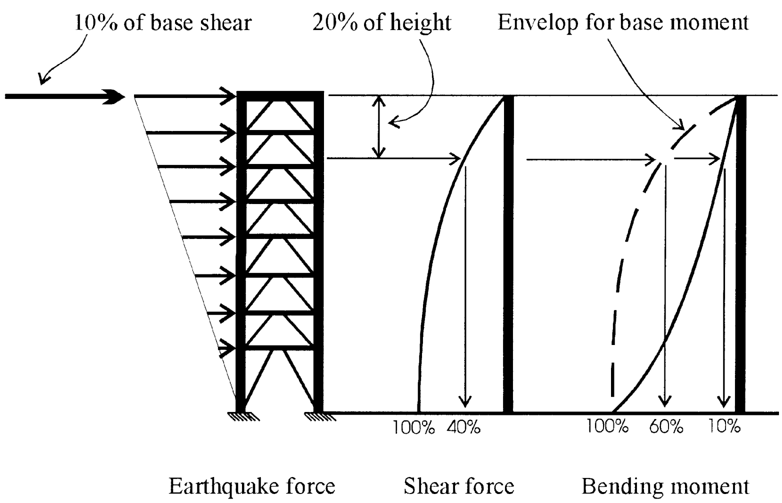


Figure 1. A code-based approach in distribution of earthquake force in buildings

3. PARTIAL MASS ISOLATION

The same as base isolation, partial mass isolation uses a relatively flexible layer that consists of spring-damping components somewhere in the height of the building but not at the level of foundation [as shown in Figure 2(b)]. The idea is the same, to change dynamic characteristics of the building in order to reduce the amount of input energy imparted by the structure during an earthquake.

In spite of the apparent similarities between the two isolation methods, partial isolation is different from base-isolation technique in a number of ways. Similarities and differences between these two approaches are categorized in the following sections.

3.1. Single degree of freedom versus multi-degrees of freedom

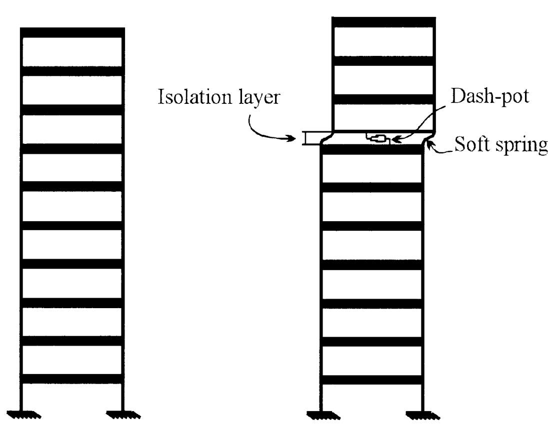
Base isolation is meant to ideally reduce a multi-degrees-of-freedom structure to a single-degree-of-freedom system. However, in partially isolated systems this will not be the case because only a part of the mass has the privilege of using excessive flexibility provided by the isolator. No matter how flexible the isolation layer is, the remaining part of mass cannot directly enjoy from this additional flexibility and higher mode effects are inevitable. In fact, partial isolation only changes one multi-degrees-of-freedom system to another with different characteristics.

The inherent simplicity in mechanism of a mass-spring model extends, in general, to base-isolation concept in a structural system. In partial isolation, however, the concept of modal shape and periods has to be employed to be able to describe the behaviour of the system.

3.2. Earthquake input energy

In single degree-of-freedom systems one of the most desirable aspects in the application of the isolator is to push the natural period of vibration to a less intensive zone of the earthquake's spectrum. In this case the system receives less force and, in most cases, less input energy from the earthquake. In general, this concept is also applicable to base-isolated buildings because the first mode of vibration of these systems usually accompanies with almost all of the mass of the structure, representing predominantly a single-degree-of-freedom system.

In partial isolation there is no assurance to reduce the level of earthquake input-energy transferring to the system. Although this method pushes the first mode of vibration to a less intensive zone of the earthquake



(a) - Shear building (b) - Shear building with PMI

Figure 2. Partial mass isolation in a shear building

spectrum, but this mode has only a fraction of the total mass and its contribution in the response of the structure is not substantial. The system now possesses a new set of higher modes (with considerable amount of mass) which are sometimes close to the high-energy zone of the earthquake's spectrum. In general, it is quite possible for partially isolated systems to receive more input energy from the earthquake than a non-isolated structure. Although this fact does not sound supporting to the idea of partial isolation, it is not considered a major drawback after a closer look at the concept of input energy.

Structures with partial isolation are supposedly equipped with large viscous damping devices to absorb the energy of the earthquake and only that portion of input energy which does not dissipate through viscous damping mechanism transfers to the structural components of system. Partial isolation has targeted this part of input energy as its goal in energy reduction of the system. In this approach, no matter how big the total input energy is, the share of structural components of the system from this energy is always small.

3.3. Damping requirements

In single-degree-of-freedom systems having a large damping ratio in isolation mechanism increases the level of force and energy transmitted to the system in the range of designing frequencies for the isolator (see, for example, Reference 1). Theoretically, a flexible isolation layer with low damping ratio is the most effective system for single-degree-of-freedom systems. The same concept also applies to base-isolated structures. Having a high damping ratio in the isolation layer not only increases the level of force and input energy in the system, but it also triggers higher mode effects and causes input-energy transmission to the structural components of the building. A properly designed base-isolated system is literally manifested as a flexible low damping-ratio mechanism, enable to reduce input energy of the earthquake while preventing transmission of this energy to the structural components of the building (by suppressing higher mode effects). Damping in this system is only required to prevent the possibility of resonance and to control ambient vibration of structure.

In partial isolation, depending on the earthquake's characteristics, total input energy transmitted to the system can be higher than that in a comparable non-isolated structure. To improve the structural performance of a building, this energy must be damped effectively within the isolation mechanism. Modal shapes of partially isolated structures have an important characteristic which enables them to dissipate a large amount of energy through a viscous damping device integrated into the isolation layer. All major mode shapes exhibit a large relative displacement at the level of the isolator, providing high relative velocity between adjacent parts of the isolation mechanism. A large-capacity viscous device can use this relative movement to effectively dissipate the input energy of the earthquake.

Partial isolation can be distinguished by its multi-functional damping requirements. Viscous damping in this technique manages to absorb a large amount of input energy and it controls the relative displacement of the isolated parts of the building. A properly designed damping mechanism can also suppress ambient vibration of the structure. To emphasize on the importance of viscous damping in this approach, hereinafter isolation layer is referred to as Viscous Mass Isolator (VMI).

3.4. Design versatility

In contrast with base isolation, partial isolation provides numerous options for the designer to adjust his/her plan with the desirable performance of building. Location of the isolation layer (and perhaps the number of layers to be used) is the basic guideline in the design process. Depending on where at the height of building the isolation layer has been placed, the behaviour of the structure varies from an ordinary base-isolated system to a building equipped only with a simple mass-damper mechanism. Stiffness and damping requirements for the VMI layer and if an active or passive system is preferred are among other design options. Integration of active control systems with partial isolation provides the required technological edge for this technique to be more effective and extends its application to high-rise structures.

4. NATURAL MODE SHAPES

Partial isolation in tall buildings changes the basic dynamic characteristics of the structure. These changes are primarily manifested in shifting natural periods of the building and also creation of a new set of modal shapes in the system. In an example, a ten-storey (30 m in height) shear building shown in Figure 2(a), has been chosen for numerical investigation. This structure is a simple uniform building with equal masses in all the floors and equal column stiffness in all the storeys. The height of the building categorized it as the ultimate edge for application of the standard base-isolation technique. The numerical model of the structure consists of simple elastic beam elements. Boundary conditions of nodes have been selected to properly simulate the behaviour of shear buildings. It is assumed that, the structure without isolator has a moderate realistic damping ratio (proportional mass-stiffness damping) for each mode. The results of a simple modal analysis with Program Drain-2DX[2] for the first four modes of the structure is shown in Figure 3(a).

In this figure parameter ϕ_i refers to a typical mode shape, T_i is the natural period of mode ϕ_i and ζ_i the damping ratio of that mode. Parameter β_i is the mass participation factor for base shear in mode ϕ_i given by the following equation:

$$\beta_i = \frac{1}{M} \frac{L_i^2}{M_i} \tag{1}$$

in which L_i is defined as the earthquake modal participation factor for mode ϕ_i and M_i the generalized modal mass[1] of that mode. M is the total mass of building. Parameter β_i indicates that, if an earthquake excites

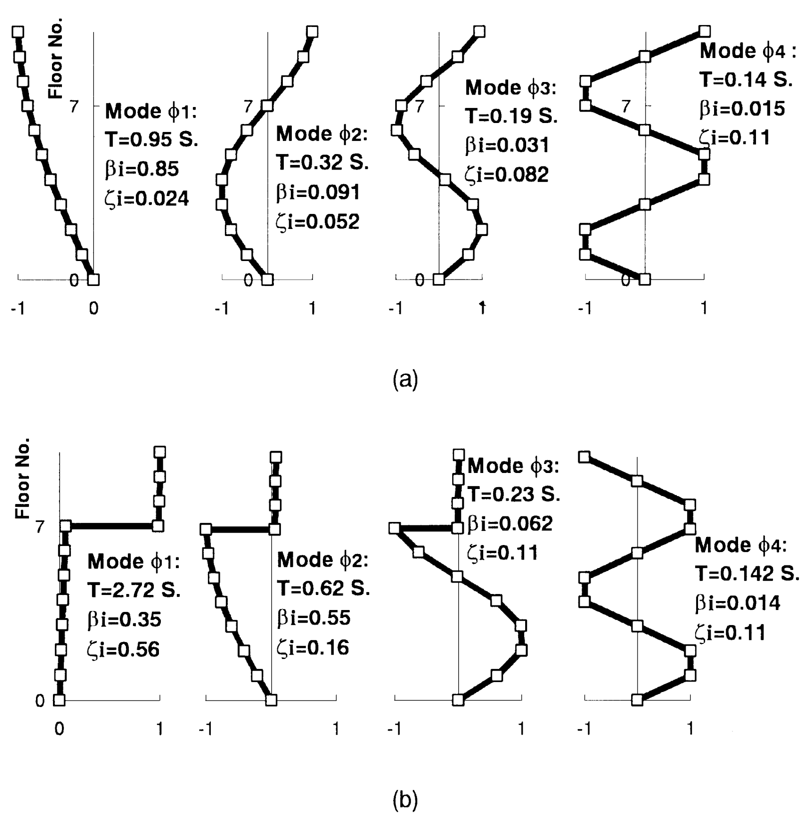


Figure 3. Results of modal analysis for medium-height shear building

a particular mode of vibration, how much of the total mass of the building will contribute in generating base shear in that mode. This parameter can be considered as a measure for the importance of each mode.

In the next step, the top three storeys of the building (30 per cent of total mass) are isolated by a viscous mass isolator. Stiffness of the isolator has been chosen in order to shift the first natural period of the structure to more than 2·5 s. The isolation system is a simple horizontal spring dash–pot mechanism located on top of the seventh floor connecting the bottom part of structure to its top isolated part as shown in Figure 2(b). A zero-length connection element simulates this layer in the numerical model of the structure. Isolation parameters are proportioned to provide a large damping ratio for this layer. As an estimation on the rate of damping, it is roughly chosen to provide 50 per cent of critical damping for the first mode of vibration ($C = 2\zeta M\omega$, where $\zeta = 0{\cdot}5$), considering only the isolated part of mass in this estimation.

In the new system, as it is shown in Figure 3(b), a totally different set of mode shapes has been created. The first mode exhibits a large natural period compared with the first mode of the original structure. This mode has more than $\frac{1}{3}$ of mass participation factor for base shear β_i, almost equal to the magnitude of isolated mass, indicating an effective partial isolation. The second mode of the isolated structure now is the main mode of the new system with 55 per cent of mass participation factor β_i (30 per cent less than the main mode of the original configuration).

Modal shapes of the new system are indicating a phenomenon similar to Inverted isolation. It seems that, the mass at the top remains fixed and acts as a base from the top for the remaining structure at the bottom. By a closer look, the modal shapes of building are quite similar to the natural modes of a base-isolated system, but they look inverted. The only parameter differentiating between base isolation and partial isolation modal shapes is the mass participation factor β_i. This factor in base isolation is very big for the first mode but quite small for other modes, indicating a behaviour similar to single-degree-of-freedom systems. In partial isolation, however, the system has at least two or three major modes with comparable values for β_i which is a unique feature in the seismic behaviour of structures.

Most of the modal shapes are showing a large displacement at the level of the isolator. This sliding gap between two adjacent isolated parts of the structure provides the required high relative velocity for implementation of viscous damping devices. The effectiveness of viscous devices in increase on the rate of the damping ratio of the structure has been demonstrated in the same example. Program Drain-2DX approximately calculates equivalent modal damping ratio for each mode. The method of calculation[2] is based on the ratio of energy absorption by damping to the maximum strain energy of the system. Results, shown in Figure 3(a) and 3(b), indicate that wherever one of the natural modes of the system exhibits a large relative displacement at the level of isolator, there is a substantial increase in the damping ratio of that mode (particularly in those with large mass participation factor β_i).

Large damping ratio creates stable relative displacement for isolated parts of the structure. In fact, the isolation mechanism behaves similar to a displacement seismograph (which is usually a highly damped system with $\zeta = 0{\cdot}5$). This similarity implies that, maximum relative displacement of the isolated parts of the structure can be kept in the order of the earthquake's peak displacement magnitude by using a high damping ratio. However, a disproportionately large damping mechanism must be avoided because it locks the required movement between two isolated parts of structure, eliminating the function of mass isolation.

Partial isolation creates a radically different modal shapes as well as damping ratios and mass participation factors. These changes makes the simplified assumptions on superposition of maximum modal responses in classical spectrum analysis invalid (see, for example, Reference 1). In fact, the existence of a large damping device in the system creates a damping matrix which does not even possess the required dominant diagonal feature. As a result, a strong coupling between the modes of vibration would be expected. Consequently, modal shapes of this system are of no use in uncoupling of the equations of motion and application of modal technique in time-history analysis of the structure is also not permissible. To determine the response of this highly coupled system to any given forcing function, a full fledged direct time-integration analysis is required.

Intuitively, the damping device located between two segments of the structure causes modal interaction. Damping of higher modes is at the expense of exerting inertial energy to the isolated mass on the top of the

building which acts as the support for the reaction of the damping device. This reaction force excites the first mode of the system and causes modal interaction.

5. DYNAMIC ANALYSIS

Three types of structures have been used for time-history analysis in this study. Among them are a medium-height shear building, a tall shear building and a tall flexural structure. The numerical model for all the structures are quite simple without any special detail and analysis has been carried out without parametric study on various options in design.

Simple direct time-integration analysis for all the specimens has been performed. In analysis, four different earthquake records have been used, three of them quite well known in designing of tall buildings (El-Centro, Hachinohe and Taft). The fourth one (San-Fernando earthquake S16E), has been intentionally chosen for its rather unusual characteristics with a very high peak ground acceleration (1148 cm/s^2) and peak displacement (37·7 cm) in a short duration.

Displacement time history of the structure (measured at the bottom level of the isolator) has been monitored and compared with displacement at the same level in a similar structure without isolator. To justify the practicality of design, the relative displacement of the top and bottom of the isolator has also been recorded, illustrating misalignment of two adjacent isolated parts of structure during an earthquake. As a typical example, only time-history responses for the El-Centro earthquake are shown in the figures.

In order to describe the behaviour of partial isolation in the structures, some other measures have been defined. These are a set of non-dimensional parameters indicating the effectiveness of partial isolation in reducing energy, displacement and forces in structures. Parameter $\lambda_T = ET_{PMI}/ET$ is the earthquake total input-energy ratio calculated based on the total input energy with partial isolation (ET_{PMI}) and without it (ET). Parameter $\lambda_S = ES_{PMI}/ES$ is the same ratio but for input energy transmitted to the structural components of building. Parameter $\alpha_I = DI_{PMI}/DI$ indicates the ratio of maximum displacements at the isolator level and $\alpha_T = DT_{PMI}/DT$ stands for maximum displacement ratio at the top of the structure. The effectiveness of partial isolation in reducing shear force and moment at the first storey of the structure is defined by parameters $\beta_S = SH_{PMI}/SH$ and $\beta_M = M_{PMI}/M$, respectively. Maximum lateral deformation of the isolator during vibration ΔU_I, is also used as a measure for serviceability and feasibility of design. Results of analysis in terms of these performance parameters for all the specimens and all the earthquakes are tabulated in Table I.

Energy calculation in this study is based on the Program Drain-2DX method of energy calculation.[2] This program reports the total amount of external work on the structure during an earthquake which is a measure for total input-energy estimation (the work done by rigid-body translation of the system on ground movement is ignored). This value has been used in calculation of ET, ET_{PMI} and λ_T. The program also reports the work done in each element groups. These values were used in calculation of energy transmitted to the structural components of the building (parameters ES, ES_{PMI} and λ_S).

5.1. *Medium height shear building*

In this phase of study structures shown in Figures 2(a) and 2(b) with the same natural period and mode shapes [as illustrated in Figures 3(a) and 3(b)] are chosen for dynamic analysis. Results of time-integration analysis of the partially isolated structure subjected to El-Centro earthquake (shown in Figure 4) indicates a substantial decrease in displacement of the building at the level of the isolator (compared with non-isolated structure). This reduction in displacement is not at the cost of large relative movement between two isolated parts of the structure (as is shown in the bottom part of the same figure). Results of analysis for three other design earthquakes in Table I indicates that, the only case in which relative movement between isolated parts of the structure (or lateral deformation of isolator, ΔU_I) becomes large, is the case of San–Fernando earthquake which is considered as an unusual event.

Table I. Summary of time-history analysis of all buildings

	λ_T	λ_S	α_I	α_T	β_S	β_M	ΔU_I(mm)
Medium height shear building							
Subject to:							
El-Centro (S00E)	0·89	0·18	0·42	0·46	0·44	0·44	109·6
Hachinohe (EW)	0·93	0·12	0·26	0·47	0·32	0·32	106·5
Taft (EW)	1·38	0·27	0·55	0·82	0·62	0·62	54·3
San-Fernando (S16E)	0·67	0·11	0·35	0·77	0·45	0·45	319·2
Average	0·97	0·17	0·39	0·63	0·46	0·46	147·4
Tall shear building							
Subject to:							
El-Centro (S00E)	1·17	0·37	0·55	0·58	0·55	0·55	164·1
Hachinohe (EW)	0·66	0·15	0·39	0·51	0·43	0·43	195·3
Taft (EW)	1·40	0·45	0·71	0·81	0·67	0·67	69·6
San-Fernando (S16E)	1·92	0·61	0·86	1·02	0·73	0·73	408·0
Average	1·29	0·39	0·63	0·73	0·59	0·59	209·3
Tall flexural building							
Subject to:							
El-Centro (S00E)	0·91	0·25	0·63	0·63	0·64	0·62	95·8
Hachinohe (EW)	1·04	0·21	0·69	0·74	0·49	0·37	113·2
Taft (EW)	1·21	0·34	0·63	0·75	0·80	0·60	68·0
San-Fernando (S16E)	0·85	0·24	0·71	0·81	0·49	0·37	313·1
Average	1·00	0·26	0·66	0·73	0·61	0·49	147·5
Global average	1·09	0·27	0·56	0·70	0·55	0·51	168·1

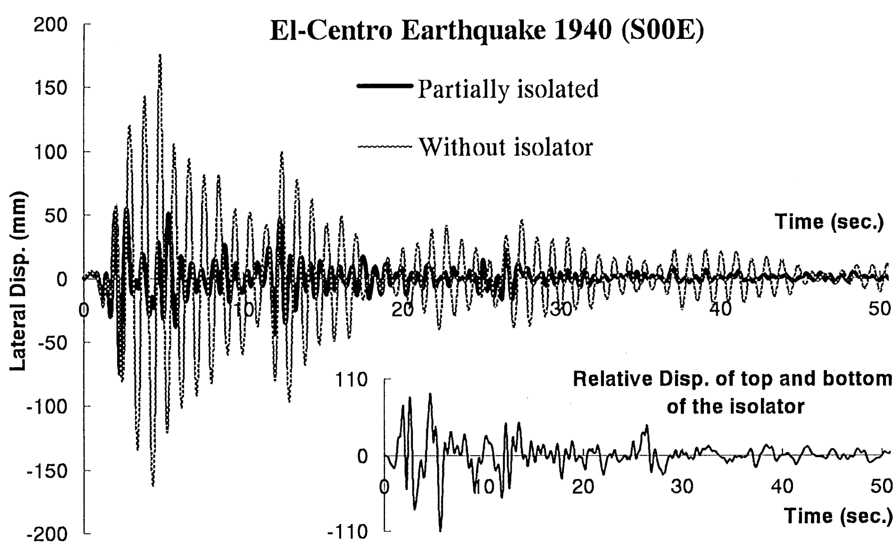


Figure 4. Displacement time history at the level of the isolator for medium-height shear building

To control this relative displacement a simple increase in damping ratio will solve the problem. But such reduction of relative displacement reduces the effect of isolation and increases the level of load on the structure. A more effective approach is to use non-linear damping devices. This issue will be discussed later.

As is shown in Table I, for medium-height shear building, on average, there is not a significant change in total input energy reduction of partially isolated system ($\lambda_T = 0{\cdot}97$), but there is a substantial decrease on the amount of input energy transferred to the structural components of the building ($\lambda_S = 0{\cdot}17$). Shifting the natural period of structure has not pushed the new system to a low intensive zone of the earthquake's energy spectrum and in one case (Taft earthquake), the partially isolated system has received even more input energy ($\lambda_T^{Taft} = 1{\cdot}38$). However, regardless of the amount of total input energy, the share of the structural components of the system from this energy is insignificant.

Results of the analysis also indicates that, reduction in input energy is not necessarily proportional to the reduction of maximum displacement and forces in structure. While input energy is reduced on average to about 17 per cent of the energy of a non-isolated system, the ratio of maximum displacement and/or forces in the structure has not been dropped to less than 39 per cent in this example. This is the sign of a highly damped system. In general, damping reduces the amplitude of vibration but during the time and it is not quite effective in reducing maximum displacement and forces.

To be able to use the full potential of reduction in input energy of the structure, a mechanism to control maximum forces is required. Acceptance of localized plastic behaviour of members can be justified for this purpose. In a highly damped system, the fast reduction in amplitude of vibration results in decreasing the number of reoccurrence of maximum forces in structural members. Thus, the chance of rupture in the system's components because of low cycle fatigue (which plagues the plastic behaviour of members) would be minimal, resulting in a more reliable performance for the structure in the range of plastic behaviour.

The ratio α_T is a measure for displacement reduction at the top of the structure and indicates that in spite of the application of a flexible layer in the building, displacement at the top (maximum displacement in this system) has been reduced.

5.2. *Tall shear building*

The next example is a 50-storey shear building with the same mass, stiffness and height for all the storeys. The total height of building is 150 m. Numerical model is similar to the previous example. The isolation layer is applied on 20 per cent of the height of building and it is located on top of the 40th floor of the structure. The proportion of isolated mass has been reduced in order to keep its height to a maximum ten storey limit. Damping and stiffness of this layer has been chosen proportional to the previous example (considering the change in mass of the isolated part of structure).

Results of modal analysis for both non-isolated and partially isolated structures are shown in Figures 5(a) and 5(b), respectively. In this example partial isolation has created a second mode of vibration with a large mass participation factor ($\beta_2 = 0{\cdot}39$) at the range of the natural periods which may have high-energy content in some earthquake's response spectrums ($T_2 = 1{\cdot}66$ s). The system now offers two major modes of vibration instead of one in an ordinary structure. This unusual feature may cause more earthquake input energy to be entrapped within the system (compared with the case with only one major mode).

The result of the time-history analysis of the structure subjected to the El-Centro earthquake is shown in Figure 6. From Table I, it is clear that, the performance of the system is much lower than the previous example. One of the reasons is the fact that, only 20 per cent of the mass in this example has been isolated compared with 30 per cent in the example for the medium height building. The major reason, however, is the new natural period and mode shapes of the system. Having two major modes creates a system susceptible in receiving larger amount of input energy from the earthquake. This has happened, for example, in the case of San-Fernando earthquake by almost doubling the total input energy of the system. Nevertheless, results of the analysis indicates a considerable improvement on the performance of the structure and the share of structural components of the system from total input energy is still quite small.

5.3. *Tall flexural structure*

Last example is a tall flexural building of 150 m height in 50 storeys (with equal mass and stiffness). In the numerical model, boundary conditions for each floor has been chosen free to rotate to simulate the flexural

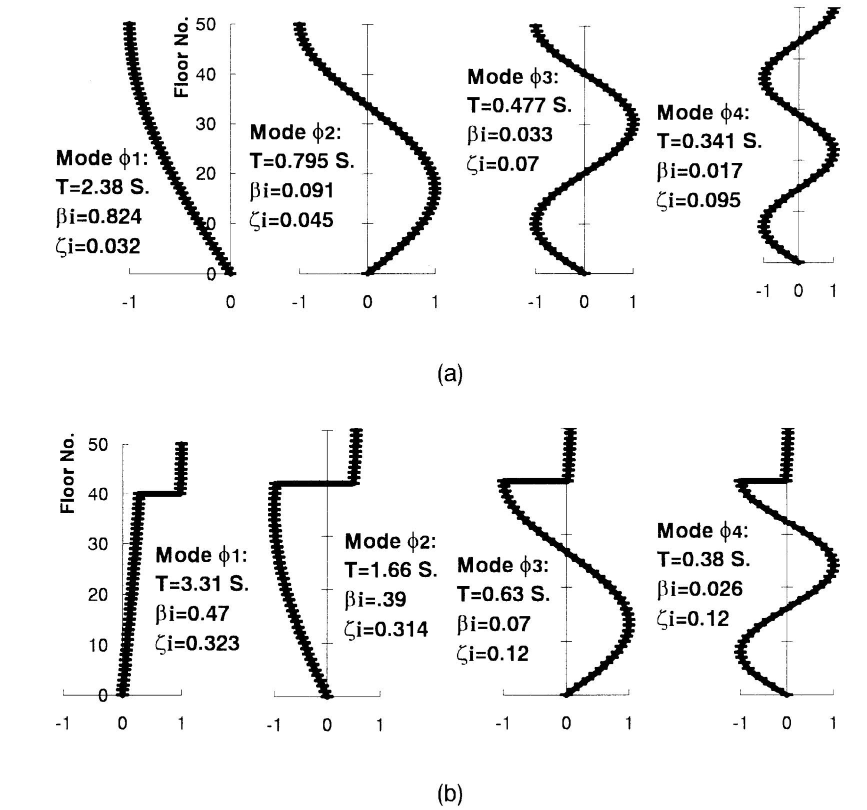


Figure 5. Results of modal analysis for tall shear building

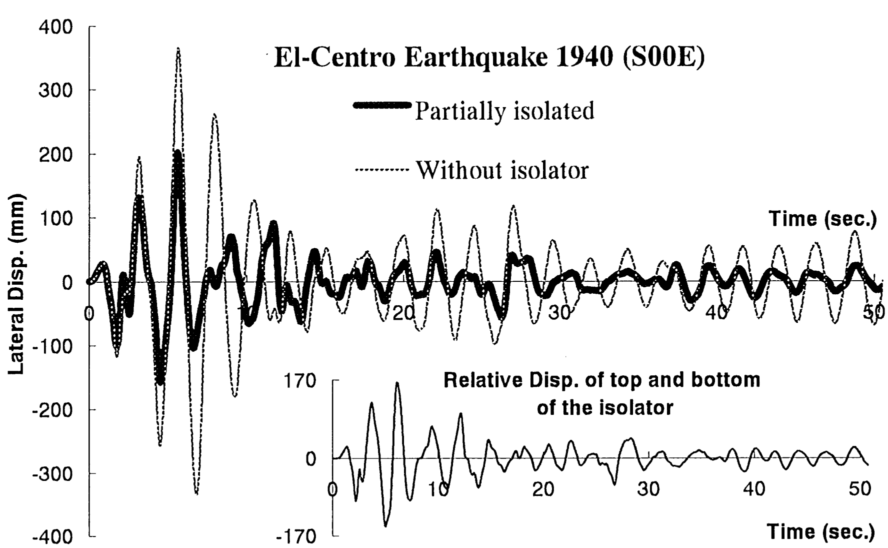


Figure 6. Displacement time history at the level of the isolator for tall shear building

nature of the structure. Figure 7(a) shows the result of the modal analysis of the building. Having a very long first-natural period has been intended to simulate the behaviour of a tall high-rise structure.

The same isolation mechanism has been applied, again on 20 per cent of the height of the building. The isolation layer in this case must be more flexible than that in the previous example in order to function as an isolator for the first mode (which already has a very long natural period). With the same amount of isolated mass, stiffness of isolator has been reduced to $\frac{1}{3}$ of the previous example (which is deemed to be a potential technical problem) while damping capacity was kept unchanged.

The results of the modal analysis of this structure is shown in Figure 7(b). Although the first mode still incorporates the sliding effect of the isolation layer, the ordinate of this slide is not as big as those in the previous examples. This indicates that, isolation is not fully functioning for the first mode of the system. But by referring to the same figure, it is obvious that, partial isolation is still quite effective for other modes.

Figure 8 shows the response of the structure subjected to the El-Centro earthquake. Results of the analysis for all design earthquakes (shown in Table I) indicates a better performance than that in the previous example, particularly in the criteria of earthquake input energy. This is mostly due to the fact that, partial isolation has not created another major mode of vibration in the region of high-energy content of the earthquake's spectrums. First two modes of the system with 70 per cent of mass participation factor for base shear (β_1 and β_2) are both located in the range of long natural periods ($T_2 = 2{\cdot}6$ s).

Another point in this example is the more pronounced reduction on the ratio of maximum moments β_M, compared with the same ratio for maximum shear forces β_S. This observation solidifies the conception of the code-based approach (discussed before) in which a higher reduction of moment compared with shear is

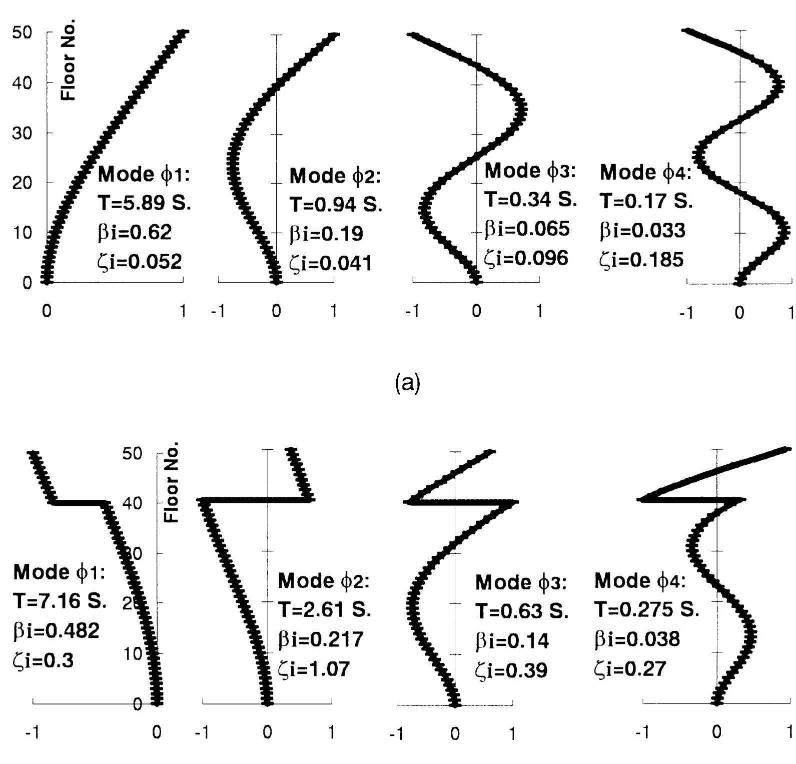


Figure 7. Results of modal analysis for tall flexural building

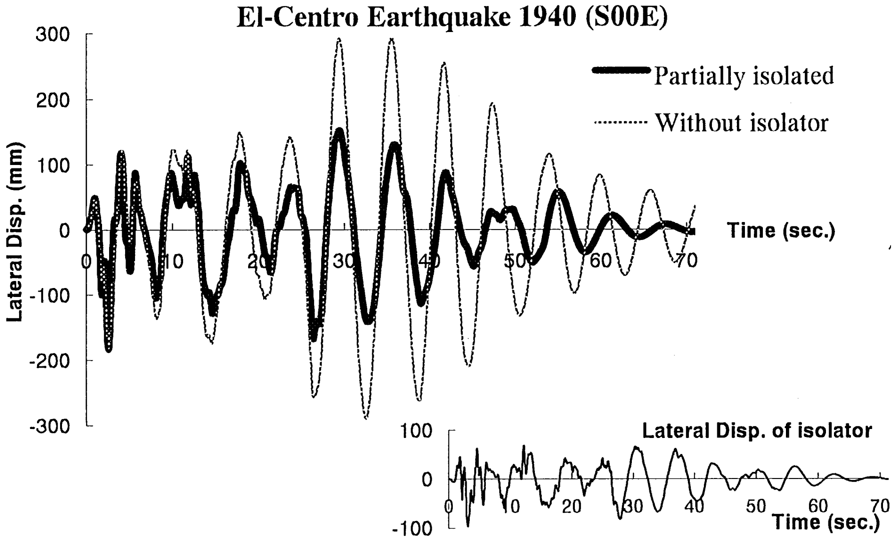


Figure 8. Displacement time history at the level of the isolator for tall flexural building

anticipated by reducing the earthquake force at the top of the building. In previous examples this fact has not been shown because structures were assumed as perfect shear buildings.

6. APPLICATION ON SEISMIC RETROFIT

By new findings in the area of seismic effects on buildings, an increasing number of existing structures are facing the necessity of seismic retrofit. There is not yet a practical method for a large number of buildings to improve their performances in the case of an earthquake incident. Partial isolation can be a great help for such cases because it does not need any major changes in existing buildings and it can be applied on structures without interruption in their daily operation. In an ideal case, it is possible to apply this technique on top of the structure simply by adding to the number of storeys. This is considered in fact, a lucrative retrofit approach in the places in which land for new buildings is expensive. Partial isolation can also be applied in the mid-height of the existing structures by a more complicated process.

As a preliminary example, a comparison between a seven-storey shear building and a ten-storey one with partial isolation on top of the seventh floor has been performed. This can be interpreted as adding three more storeys on top of the existing seven-storey structure. Here again, the same numerical model for the medium height shear building (used in the first example) has been employed. Time-history results for displacement at the seventh floor in the retrofitted structure subjected to the El-Centro earthquake is shown in Figure 9 and compared with the original seven storey structure without isolation. Results of analysis for all designed earthquakes (in terms of performance parameters) are tabulated in Table II.

On average, partially isolated ten-storey system has received considerably more input energy than the original seven-storey building, but the share of structural components of the system from this energy remained small. Reduction in displacement and forces are fairly modest considering that, retrofitted structure has ten storeys instead of seven in the original configuration (the total mass of the new structure is about 40 per cent more than before).

The results are quite promising but it may not look convincing. Intuitively, adding three more storeys to the existing building is an attempt to control the first mode (and also other modes) of vibration of the original structure by a damping mechanism located on the top of the building. Therefore, from a structural point of

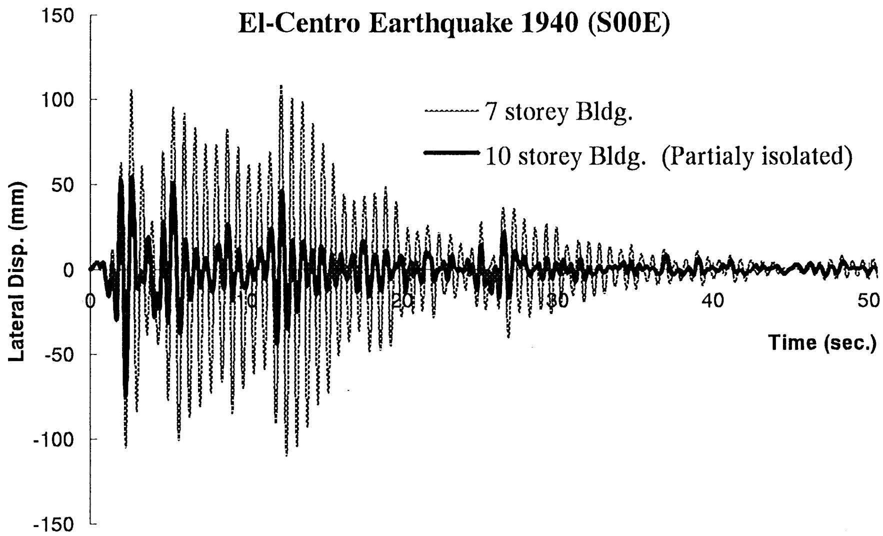


Figure 9. Displacement time history at the seventh floor before and after retrofit

Table II. Summary of time-history analysis of retrofitted building

Earthquake	λ_T	λ_S	α_I	β_S & β_M	ΔU_I(mm)
El-Centro	0·71	0·12	0·68	0·56	109·6
Hachinohe	3·14	0·33	0·72	0·73	106·5
Taft	1·32	0·23	0·65	0·59	54·3
San-Fernando	3·36	0·48	0·93	1·09	319·2
Average	2·13	0·29	0·75	0·74	147·4

view, the additional three storeys are solely meant to be as a support for the reaction of the damping mechanism. In the new system, the mass of added storeys are attributed mostly to the first mode of vibration which is properly isolated by a long natural period [the new system is the same example as shown in Figures 2(b) and 3(b)]. The second mode of structure, which has the mass of the original building, now accompanies with a large damping ratio as it was intended, describing how energy and force transmitted to the system have been reduced.

7. PARTIAL MASS ISOLATION AND ACTIVE SYSTEMS

Restriction on the amount of mass to be isolated in a structure is one of the obstacles in application of partial isolation in high rise buildings. It is assumed that, technically it is difficult to isolate more than ten storey of a structure. In a 100-storey building this limit is about 10 per cent of the total mass which is not significant enough to reduce vibrational effects on the structure. Moreover, in structures with long natural period, isolated mass requires a very flexible isolation mechanism (to be functional in the first mode) which may not be available due to technical restrictions.

In such cases, it is possible to consider the isolation layer to be effective only for higher modes of the system and use other methods to reduce the amplitude of vibration of the first mode (for example, computer-control post-tensioning tendons or other techniques). Having accepted this, there is no need to considerably reduce

the stiffness of the isolator and a mechanism based on available technology can be adopted. In this case the isolation layer dissipates energy of higher modes and transfers their remaining energy to the first mode of the structure (which is a very slow mode and easily controllable by active control devices). The function of partial isolation in this system is similar to a Mode Isolator Device for the first mode.

The importance of higher modes in tall buildings is quite well known and has been addressed in numerous instances in the literature. One of the earliest study in this area is the work by Clough[3] in 1955. To remove higher mode effects has always been a concern in the design of tall buildings and partial isolation is capable of solving this problem without facing technical difficulties in isolation technology. If reduction of higher mode effects and prevention of shear wave propagation in structure is the major concern in the design of tall buildings, it is plausible to use partial isolation without an active system in high-rise structures.

In another view, it is also possible to fully integrate partial-isolation technique with a computer-control damping–actuator mechanism to make it an intelligent, thus a more effective and efficient system. In this case the isolated mass acts as the support for the reaction of actuator and damping devices, similar to the tuned mass damper (TMD) approach but more effectively because it uses a relatively larger mass in its operation.

8. ISOLATION COMPONENTS

It is believed that, in most of the cases, the same technology used for base-isolation technique is also applicable in partial isolation and only a refinement of the existing technology is required for adaptation. Nevertheless, this method needs more sophisticated components (i.e. low stiffness and high damping) because it deals with structures with longer natural period.

For example, one possible approach in application of partial isolation is to reduce the stiffness of one of the storeys of the building to act as the isolation layer in the structure (instead of using isolator devices). Although this method seems quite appealing from an architectural point of view, technically it needs a complicated detailed design and also delicate components to provide all the required features for a system with dependable performance.

While problems associated with development of a reliable low-stiffness mechanism are the major technical concerns in partial isolation, damping system also needs some technical sophistication. An ordinary linear viscous damping model was used in the numerical analysis of examples in this study. In partial mass isolation a high damping force reduces the effect of isolation and locks the sliding gap between two isolated parts of a structure. This phenomenon practically sets a limit on the amount of damping ratio to be used in this approach. To increase damping effects beyond this limit, a non-linear viscous device capable of rendering lower damping force along with higher energy-dissipation rate is required.[4]

In partial isolation, the non-linearity in the damping mechanism which suits this technique is rather special. Damping ratio has to be small for higher modes because of their high velocity but it must be big for the first mode at the end of its cycle where the relative velocity is small and damping force becomes negligible. High damping ratio at the end of first mode's cycle is also beneficial to the reduction of relative displacement of two isolated parts of a structure. Although technically it is considered difficult to develop a non-linear damping device with the all required characteristics, in partial isolation a simple non-linear dash-pot mechanism may adequately solve this problem.

The proposed system which is called 'Adjustable Non-linear Dash-pot' is shown in Figure 10. Although this is not an ideal solution for partial isolation, but it provides the system with the basic desired functions. The adjustability in this mechanism comes from a removable variable diameter rod implemented inside the dash-pot to control the discharge of fluid flow between two chambers of the cylinder. By changing the shape of the rod, it is possible to easily calibrate this damping mechanism for most of the required non-linearities in partial isolation (also other applications). Technically, this system is extremely simple and quite easy in manufacturing.

In general, non-linearity in a damping mechanism can be written as

$$F_c = C \cdot |\dot{u}|^{\alpha} \cdot f(u)\,\mathrm{sgn}(\dot{u}) \tag{2}$$

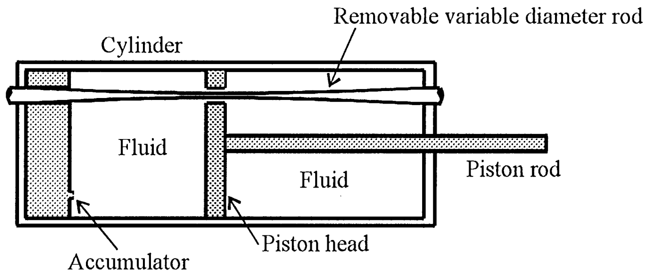


Figure 10. Adjustable non-linear dash-pot

in this equation F_c is the damping force, C the damping constant, $\dot{u}$ the velocity, $f(u)$ the function of displacement and α the non-linearity parameter. In a linear damping, both α and $f(u)$ are equal to one. Non-linearity in the proposed damping system is mainly the result of displacement function $f(u)$ in the above equation. The damping mechanism shown in Figure 10 provides low damping ratio in the middle part of the dash-pot (by a larger opening for passage of fluid) to serve for higher modes and also where the first mode has the highest velocity (to reduce maximum damping force). However, as it was intended, it offers a higher damping ratio (by blocking the flow of fluid) at the end of the first mode's cycle. The major shortcoming in this system is the fact that, it does not provide a low damping ratio if higher mode's attack happens to be at the end of the first mode's cycle.

In partial isolation the use of hysteritic damping or any other frictional-type damping is not recommended. First of all, because of the incorporation of bilinear stiffness, it can not properly damp the higher mode effects. Also, bilinear stiffness in the isolation layer eliminates one of the most desirable features of partial isolation in reducing ambient vibration of a building. In addition, as it was mentioned before, hysteritic damping is not effective in systems with long natural periods unless a large relative displacement occurs. Technical restrictions on lateral displacement of the isolator does not provide the required room for implementation of an effective hysteritic damping in partial isolation.

The amount of energy dissipation in viscous damping devices would be large and the system has to be designed to tolerate the generated heat throughout the vibration process without a considerable change in its characteristics.

9. IMPLEMENTATION OF PARTIAL ISOLATION

Having two moveable parts in a structure causes a series of architectural and technical problems. In order to have all utilities connected throughout the vibration process, a flexible connection for all cables and pipes in the building between its two isolated parts is required. Technically, this is not considered as a problem. Even low standard flexible connections are acceptable for this application because a major relative movement is not likely to occur frequently. Also, in the case of an earthquake, repairing the inflicted damage to the utility connections would not be complicated due to easy access to the damaged area. However, the concept of flexible connection for elevator shaft needs more elaboration. A simple solution for this problem could be enlargement of elevator shaft in the first storey next to the isolator.

10. CONCLUSIONS

Partial mass isolation is a method proposed for seismic design of structures in the range of medium height to tall buildings. Although it is simply an extension of the base-isolation method, it behaves differently by dissipating earthquake input energy through viscous damping devices instead of reducing energy by lengthening the natural periods of the structure. Meant originally for the range of medium-height buildings,

the capability of partial isolation to adjust with different applications in high rises and seismic retrofit of structures is quite promising. Preliminary results of numerical investigations in this study indicates an impressive performance for partial isolation technique in reducing seismic effects on a variety of structures. It is believed that, a more detailed analysis is required to solidify these results and in order to establish this technique.

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